Traxion: A Tactile Interaction Device with Virtual Force Sensation

Jun Rekimoto
Interfaculty Initiative in Information Studies, The University of Tokyo
7-3-1 Hongo, Bunkyo-ku, Tokyo 113-033, Japan
Sony Computer Science Laboratories, Inc.
3-14-13 Higashigotanda, Shinagawa-ku, Tokyo 141-0022, Japan
rekimoto@acm.org

ABSTRACT
This paper introduces a new mechanism to induce a virtual force based on human illusory sensations. An asymmetric signal is applied to a tactile actuator consisting of an electromagnetic coil, a metal weight, and a spring, such that the user feels that the device is being pulled (or pushed) in a particular direction, although it is not supported by any mechanical connection to other objects or the ground. The proposed tactile device is smaller (35.0 mm × 5.0 mm × 7.5 mm) and lighter (5.2 g) than any previous force-feedback devices, which have to be connected to the ground with mechanical links. This small form factor allows the device to be implemented in several novel interactive applications, such as a pedestrian guide system that includes a finger-mounted tactile device or an (untethered) input device that features virtual force. Our experimental results indicate that this illusory sensation actually exists and the proposed device can switch the virtual force direction within a short period. We combined this new technology with visible light transmission via a digital micromirror device (DMD) projector and developed a position guiding input device with force perception.

Author Keywords
Input devices; tactile interactions; force feedback; perception; illusion

ACM Classification Keywords
H.5.2. Information Interfaces and Presentation (e.g. HCI): User Interfaces

General Terms
Input devices; Tactile interactions; Illusion

INTRODUCTION
Haptic sensations play a very important role in our daily life. The sense of touch enables us to physically manipulate an object smoothly, rapidly, and accurately. We naturally and extensively use this sense every day during moments of physical interaction. Several systems have been proposed for incorporating haptic feedback into human-computer interactions. While normal graphical user interfaces (GUIs) rely mainly on visual information, these systems use synthetic haptic sensations as one facet of human-computer interaction.

There are two types of haptic feedback. In one type, which we call "force-feedback," a real-world physical force is created. Devices belonging to this category often use mechanical rods [8, 10], motor-controlled strings [6], or other physical mechanisms. In the second type, called "tactile-display," physical sensations are created as an additional feedback method. Examples of devices in this category include mice or gamepads with vibrators and touch panels with an actuator that adds a tactile "click" feeling to an interaction [5, 12]. Both types have their own advantages and disadvantages. Force-feedback type devices normally require a mechanical component linked to heavier objects, or to the ground. Its working space is therefore limited, and because of its bulkiness, mobile use is not practical. In contrast, tactile-display devices can be smaller and lighter, but they can create only a vibration, not a force.

There have been a few previous attempts to create force without using mechanical support. We can feel a force when trying to rotate a friction wheel because of a "gyro" effect. Nakamura et al. combined two or three eccentrically weighted rotors to generate an illusory sensation of force [14, 11, 4]. Amemiya et al. also proposed a device that creates a perceptual attraction force, based on the asymmetric actuation of a mechanical weight [2, 3]. These devices are based on the asymmetry of the relationship between stimulation and perception in the human. When people use such a device, they can perceive a traction force, although there are no mechanical links between the device and other objects. However, since these devices are based on the mechanical movement of a crank, the form factor of the device is much bigger and heavier than those of tactile displays. For example, the size of the prototype device that Amemiya developed is 70 mm × 200 mm × 48 mm, its weight is 250 g, and it consumes about 30 W [2] of power for one-dimensional (1D) traction synthesis. If two or more of these devices were combined to create a two- or three-dimensional (2D or 3D) traction force, it would become even bigger and heavier.

UIST'13, October 6–9, 2013, St. Andrews, United Kingdom.

http://dx.doi.org/10.1145/2501988.2502044

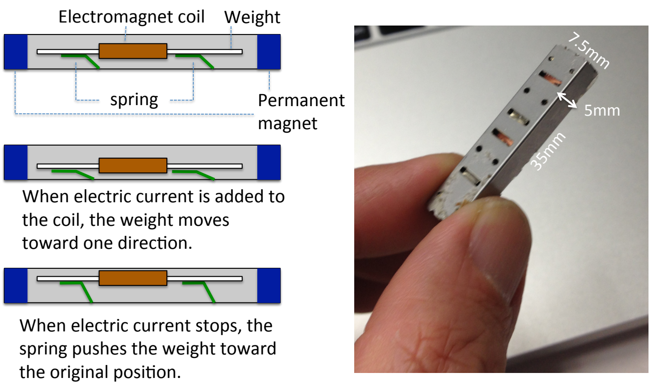

Figure 1. Configuration of the "force-reactor" tactile device

In this paper, we propose a novel device that creates a virtual force without any mechanical links to the ground being required. Furthermore, it is significantly smaller and lighter than any previous virtual force devices. Our proposed mechanism uses human illusory sensation to create the perception of a virtual force. The weight of our virtual force creation device is about 5.2 g and the size is 7.5 mm × 35.0 mm × 5.0 mm. This small form factor allows the development of several new applications using virtual force. For example, a user can be guided to a particular location by being virtually "pulled" by a device in which it is implemented. We named this tactile architecture "traxion."

TRAXION OPERATION PRINCIPLE

Traxion is a combination of an existing tactile actuator and a novel way to actuate it. We currently use an ALPS "force-reactor" [1] as the tactile actuator. This component has a structure in which electromagnet coils are attached to a metal sheet supported by a spring (Figure 1). The metal sheet is placed between two permanent magnets. When a wave signal is transmitted to the coils, the metal sheet responds to it by vibrating. After the signal stops, this vibration is suspended by the spring and the magnets within 50 ms. This short suspension time contributes to the accuracy and crispness of the tactile sensation.

While this device is effective as a tactile display, normally it does not create a force. However, we found that when an asymmetric signal is transmitted to the coils, it causes a virtual force such that the user feels as if an invisible force is pulling the device in a particular direction, or pushing it in the opposite direction. In this case, the current is applied to the electromagnet for a short period (e.g., 2 ms) to move the weight in one direction, and then is suspended. When the weight returns to the original position (which takes around 6 ms), the current is applied to the electromagnet again and the process is repeated. As a result, the movement of the weight becomes asymmetric, i.e., the movement caused by the electromagnet is fast, and the movement caused by the spring is slow. We experimented with various asymmetric signal patterns that can create a virtual force in two opposite directions. We consider that a human feels this virtual force because of the non-linearity of human force perception: the difference in the accelerations in the movement of the weight caused by

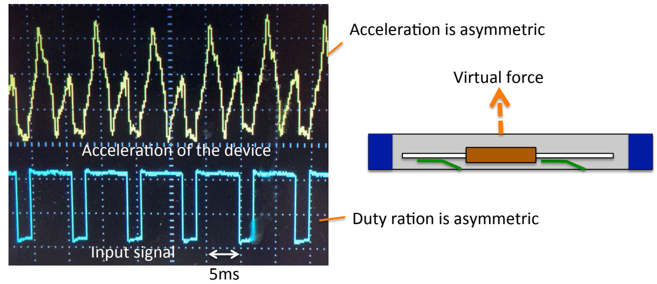

Figure 2. Operation principle of Traxion: Asymmetric electric current is added to the coil in the actuator.

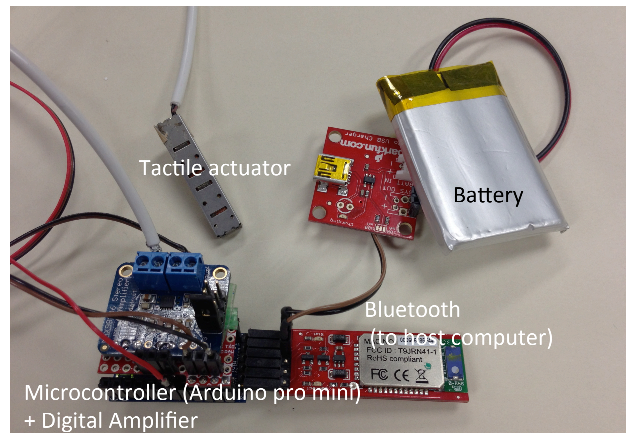

Figure 3. Traxion system configuration: the digital amplifier unit connected to Arduino microcontroller board creates a signal to drive a tactile device.

the electromagnetic coils and by the spring is not offset. Thus, the user feels a (virtual) force in one direction. By changing the duty ratio of the signal, the user can also feel a force in the opposite direction. We currently use 2 ms (ON) and 8 ms (OFF) cycle for producing a virtual force.

Since there is no mechanical component that connects the device to the ground, there is obviously no actual force; instead, there is a sensory illusion of force that the user perceives. A possible explanation for this illusion is based on the nonlinearity of human tactile sensation. As described above, the weight is moved asymmetrically by carefully controlling the ratio of the actuation signal. We assume that this asymmetric vibration causes the human sensory illusion that the object is being pulled in a particular direction.

We also found that the direction of the virtual forces, i.e., the pull force and the push force, can be changed by controlling the ratio of the electric current. This makes it possible to construct a tactile interaction device that pulls people in two directions (i.e., a bidirectional 1D virtual force device).

System configuration

The configuration of an actual virtual force-inducing system is shown in Figure 3. A microcontroller board (Arduino [9]) is connected to a digital amplifier unit that drives tactile actuators. The communication between the microcontroller and the host computer is transmitted by either a wired (i.e., USB serial) or wireless (Bluetooth serial) connection.

Comparison with previous virtual force devices

Since Amemiya et al. and Nakamura et al.'s devices also create virtual force based on human illusory sensation, it is necessary here to discuss the difference between their device and ours. The major difference is in the structure of the device. Earlier devices used a mechanical crank or rotating wheels, the size and weight of which were much larger than those of our device. In contrast, the smallness of our device allows several potential configurations, such as a finger-mounted navigation device or a tablet stylus with virtual force. In addition, the movement of the mechanical crank created an undesired vibration that masked the intended vibration to create force, and the wheel rotation created a moment effect that also caused an unintended force. Therefore, Amemiya et al. had to construct a "tandem" version in which two symmetric components were embedded to offset this undesired motion; however, the device then became even bigger and heavier.

When a mechanical wheel and cranks are used, it is also difficult to change the rotation direction (i.e., to change the direction of a virtual force) in a short period. Thus, in practice, the device is a one-way force device. This limits the possibility of using this method for interactive applications. In contrast, our device can change the virtual traction direction in a very short period (less than 10 ms) and acts as a bidirectional force feedback device. Furthermore, the smallness of our device potentially allows two or more components to be combined to conform to a 2D or 3D force feedback device within a reasonable form factor.

EVALUATION

1D virtual force: To confirm that this virtual force effect actually exists, we conducted an evaluation. Ten subjects, all students in the computer science department, participated in this experiment. A subject held the device with two fingers and electric signals were transmitted to the device to create a virtual force. The (intended) direction of the virtual force was selected randomly. The durations of stimulations were 640 ms, 320 ms, 160 ms, 80 ms, and 40 ms, and the order of the duration was also randomized. The used duty cycle was 2 ms:6 ms thus a 40 ms stimulus consists of 5 cycles. The subjects participated in five trials for each duration, and the task was to indicate when they felt a force and its direction, using a game controller stick. To avoid any possible effect from aural or visual stimuli, participants were blindfolded with a sleep mask and wore noise-cancelling headphones (Figure 4 (left)).

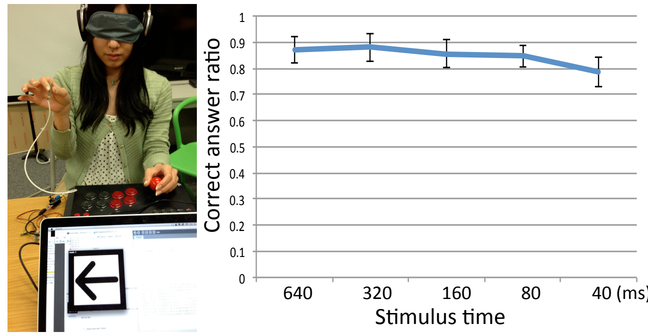

Figure 4. 1D virtual force experimental results.

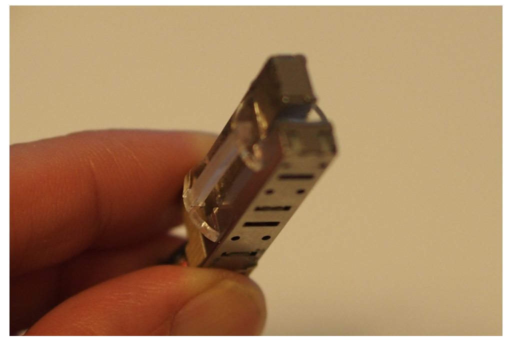

Figure 5. Configuration of 2D force device.

The results are shown in Figure 4 (right). As shown in the graph, the illusory sensation actually exists, and participants could very accurately distinguish both virtual force directions, even when the duration of the stimuli was short.

In interviews held after the experiment, most participants insisted that when they moved the device in the direction of the induced virtual traction force, the perceived force was much stronger. To illustrate a possible explanation for this phenomenon, we present an example. Assume that a real force is added to an object that a participant is holding. When the participant moves the device toward that force, the perceived force should become weaker. For example, if an object is pulled by a spring, moving the object toward the spring reduces the perceived force. In contrast, when a participant feels a virtual force, the perceived force does not alter, even when the participant moves the object toward that force. Since they did not feel the expected reduction in force, the participants therefore inferred that the added force was *stronger* than before (meaning that the decrease in the perception of the force strength is offset by the increase in the added force).

2D virtual force: The experimental results demonstrated that our proposed tactile device can create a virtual force in two directions (i.e., 1D force feedback). We also examined the possibility of combining two devices to create a 2D virtual force device. Figure 5 shows the physical configuration of such a device. We transmitted two asymmetric signals to both the devices and evaluated how the synthetic force vector was perceived.

The same ten subjects participated in this experiment as in the previous experiment and were asked to hold the device with two fingers. This time, the task was to select which of eight possible force directions they sensed. The duration of each stimulation was fixed to 640 ms, and the same duty cycle (2 ms:6 ms) was used.

Figure 6 shows the results. As shown in the graph, the correct answer ratio of the perceived direction was not as good as that in the 1D experiment, although the ratio exceeds that of random guess. This means that just combining two actuators to create a merged force vector does not suffice to realize a virtual force in arbitrary directions. This issue needs to be studied further.

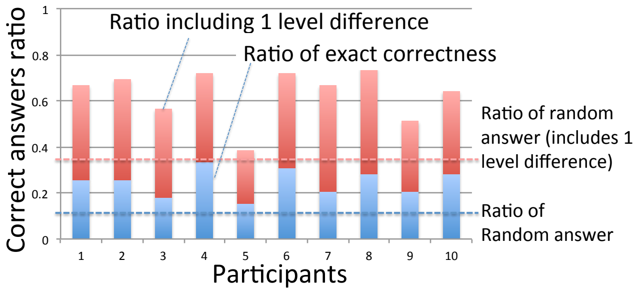

Figure 6. 2D virtual force experimental results.

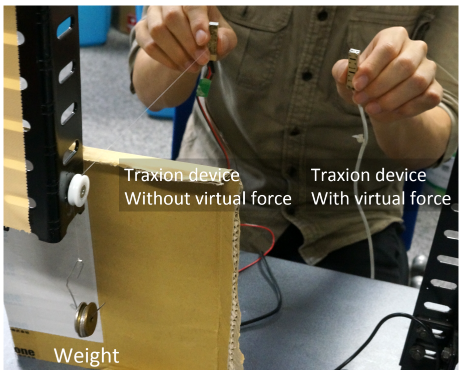

Figure 7. Estimation of virtual force strength

Estimation of virtual force strength

It should also be worthwhile to investigate the strength of the virtual force. First, as a pilot study, we designed an evaluation environment. In this experiment, a participant was asked to hold two Traxion devices, one in each hand. One device was arranged such that it induced a virtual force (using 2 ms:6 ms duty cycle), and the second device generated only a normal vibration (i.e., 5 ms:5 ms duty cycle); however, the latter device was connected to weights by a thin Nylon thread. Then, the participant was asked to compare the virtual and real force exerted by the weights (Figure 7).

The same 10 subjects participated in this experiment as in the previous ones. The average weight perceived as matching the virtual force was 29.8 g (0.292 N) and its standard deviation was 8.5 g (0.083 N).

APPLICATIONS

Virtual way finder: We feel that this device is adequate for guiding pedestrians, especially visually impaired people. By mounting the device on a user's finger, it is possible to guide the user when he or she has to turn to the left or right. We examined this possibility using the "Wizard-of-Oz" method, in which a blindfolded user with the device is guided by another user through tactile sensation (Figure 8(left)). When the pedestrian reaches the corner of a corridor, another user remotely turns on the actuator to guide the pedestrian in the intended direction.

Force-inducing input devices: Another possible application is to include virtual force in the construction of input devices. For example, a stylus for use on an interactive surface can feature force feedback without any mechanical link being used. Figure 8(right) shows such an input device. In this case, we also mounted a photo sensor and amplifier on the device to receive light from the projector.

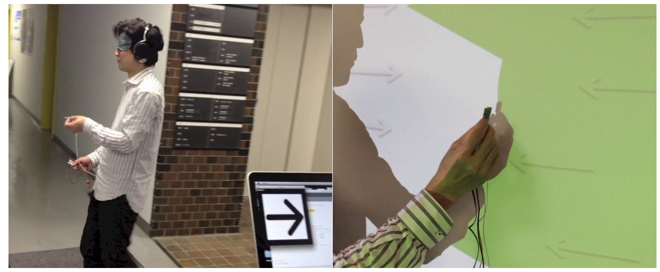

Figure 8. Traxion applications: (left) Pedestrian guide application.(right) "Virtual Force Field": An input device with virtual force feedback. A DMD projector emits a light pixel with a different temporal pattern according to its color. When the tactile device decodes this pattern and generates a virtual force accordingly, the user can feel this force.

A light projected from a DMD (digital micromirror device) projector has its own turn-on/turn-off pattern according to the color of the light. When a device can decode this pattern, and thus a virtual force is generated, it is possible to guide a user to a particular position on the screen [13] through the device. A user feels as if a virtual force is pushing or pulling the device, until it reaches to the correct position.

Although this prototype is preliminary, we consider that it is possible to develop various surface computing systems equipped with untethered force feedback input devices.

RELATED WORK

Tactile Direction Guide Systems: As discussed above, Amemiya et al. developed a virtual force feedback system based on a mechanical wheel and weight. Although this system essentially constitutes a one-way force feedback device, multiple devices can be combined to create a traction force that can be used for guiding a pedestrian [2, 3]. ActiveBelt is a tactile navigation system consisting of multiple vibrators attached to a belt [15]. When worn around the user's waist, the belt indicates a direction to the user by actuating the vibrator corresponding to the relevant direction. Our Traxion device can also indicate direction by inducing left and right virtual force to the user's finger.

Tactile Actuators: Many researchers and manufactures have developed touch panels with haptic feedback [5, 12]. We are currently using an ALPS force-reactor [1] as an actuator device, but it would be worthwhile to investigate how the asymmetric actuation of other types of tactile devices can create a virtual force, as we described in this paper. Another very different method of creating haptic sensations in free space has recently been developed [7]. This method is an extension of "spotlight audio," a technique for localizing or directionalizing audio signals using an array of transducers. In this method, a decrease in the signal frequency enables people to feel haptic sensations instead of hearing sound. Its main advantage is that no finger-mounted unit is required. Although this method is very interesting and has potential, the parameters, e.g., accuracy, sensing delay, and transducer-hand distance, that have currently been achieved are still not of a sufficiently high quality to allow realistic applications to be created.

CONCLUSIONS AND FUTURE WORK

In this paper, we proposed a tactile device that can create virtual force feedback based on human illusory sensations. Although no real force exists, users perceive that the device is pulled (or pushed) in the direction intended by the system. Since the form factor of this tactile device is smaller and lighter than that of any other previously proposed devices, it creates the possibility of developing mobile applications and untethered input devices that provide virtual force feedback. Our experimental results demonstrated that people could correctly perceive two opposite directions of virtual force.

Currently we are using only an existing tactile device and controlling a transmitted signal to create virtual force. The configuration of this device itself is asymmetric (i.e., the electromagnet is attached to one side of the metal weight and the spring is attached to the other), and therefore, the metal weight cannot be completely controlled. We feel it would be worthwhile to examine whether the electromagnet can be attached to both sides of the metal weight and whether two separate signals can be transmitted to allow the metal weight to be controlled more precisely. In addition, since the extension of our 1D system to a 2D system in which two tactile devices were combined was not very successful, we may have to create a device that has a structure in which a single controlled weight is moved in various directions, so that we can eliminate the necessity of synthesizing two vibrations.

We are also considering a system in which visible light communication and this device are combined. As briefly demonstrated in the Applications section, if the device can decode a light signal transmitted from a projector, a "virtual force field" can be created whereby a device under the projected light is guided toward a particular location. For example, an input device can be guided toward a particular object on a screen by virtual force. Surgery is another possible domain where a virtual force field can be applied to provide important support. For example, a virtual force unit can be attached to a surgical knife. This would enable the surgeon to feel the "cut-path" as a haptic sensation by means of a light line projected onto the patient's body. This cut-path information system can also be applied to other medical sensing technologies, such as ultrasonic sensing or magnetic resonance imaging.

ACKNOWLEDGMENTS

I am indebted to all the reviewers for valuable suggestions and comments to improve this paper. I also thank Ayaka Sato for video production support.

REFERENCES

1. ALPS. Alps Electric Press Release Force Reactor™. http://www.alps.com/e/news release/2005/0608 01.html, 2008.
2. Amemiya, T., Ando, H., and Maeda, T. Phantom-drawn: direction guidance using rapid and asymmetric acceleration weighted by nonlinearity of perception. In *Proceedings of the 2005 international conference on Augmented tele-existence*, ICAT '05 (2005), 201–208.
3. Amemiya, T., Ando, H., and Maeda, T. Directed force perception when holding a nongrounding force display in the air. In *Proc. of EuroHaptics 2006* (2008), 317–324.
4. Badshah, A., Gupta, S., Morris, D., Patel, S., and Tan, D. Gyrotab: a handheld device that provides reactive torque feedback. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '12 (2012), 3153–3156.
5. Fukumoto, M., and Sugimura, T. ActiveClick: Tactile feedback for touch panels. In *CHI 2001 summary* (2001), 121–122.
6. Hirata, Y., and Sato, M. 3-dimensional interface device for virtual work space. In *IEEE/RSJ International Conference on Intelligent Robots and Systems* (1992), 889–896.
7. Iwamoto, T., Tatezono, M., and Shinoda, H. Non-contact method for producing tactile sensation using airborne ultrasound. In *Proc. EuroHaptics 2008*, vol. 5024 of *LNCS*, Springer (2008), 504–513.
8. Iwata, H. Artificial reality with force-feedback: development of desktop virtual space with compact master manipulator. *SIGGRAPH Comput. Graph. 24*, 4 (1990), 165–170.
9. Mellis, D. A., Banzi, M., Cautielles, D., and Igoe, T. Arduino: An open electronics prototyping platform. In *CHI '07 Extended Abstracts*, ACM (2007).
10. Minsky, M., young Ming, O., Steele, O., Frederick P. Brooks, J., and Behensky, M. Feeling and seeing: issues in force display. *SIGGRAPH Comput. Graph. 24*, 2 (1990), 235–241.
11. Nakamura, N., and Fukui, Y. An innovative non-grounding haptic interface 'gyrocubesensuous' displaying illusion sensation of push, pull and lift. In *ACM SIGGRAPH 2005 Posters*, SIGGRAPH '05 (2005).
12. Poupyrev, I., Maruyama, S., and Rekimoto, J. Ambient touch: designing tactile interfaces for handheld devices. In *ACM UIST 2002* (2002), 51–60.
13. Rekimoto, J. SenseableRays: Opto-haptic substitution for touch-enhanced interactive space. In *CHI '09 extended abstracts*, ACM (2009).
14. Tanaka, Y., Sakai, M., Y.Khono, Fukui, Y., Yamashita, J., and Nakamura, N. Mobile torque display and haptic characteristics of human palm. In *ICAT 2001* (2001), 115–120.
15. Tsukada, K., and Yasumura, M. Activebelt: Belt-type wearable tactile display for directional navigation. In *in Lecture Notes in Computer Science. Springer-Verlag GmbH, Oct 2004*, Springer (2004), 384–399.